Tevatron Cryogenic Operations and Helium Loss

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Introduction

The Tevatron accelerator was an upgrade of an existing accelerator facility at Fermilab. The existing Main Ring accelerator became the injector to the Tevatron and they shared the same tunnel enclosure. Space constraints within the tunnel enclosure required that the Tevatron be of the smaller warm iron design. Warm iron superconducting magnets inherently have a high heat load to 4K as compared to a larger cold iron design as used in HERA, SSC, RHIC and LHC. The high heat load to 4K and the small cross-section available for cryogen passages in a compact warm iron magnet design drove the design of the cryogenic system.

Cryogenic Reliability

The Tevatron cryogenic system is a hybrid system consisting of a large central helium liquefier and twenty-four satellite refrigerators. The high heat load associated with warm iron magnets necessitated distributing refrigeration over short distances. This resulted in a satellite refrigerator capacity of 1 kW. At the time of the Tevatron design and construction, 1 kW class helium refrigerators required reciprocating expansion engines. Reciprocating expanders, as opposed to turbo expanders, have reliability and maintenance issues. As a result, the Tevatron satellite refrigerators experience downtime considerably higher than newer large scale superconducting accelerators utilizing turbo expanders and fewer large scale refrigerators. On the other hand, the Tevatron Central Helium Liquefier (CHL) is a turbo expander based

As a comparison, Table 1 shows the downtime of the Tevatron central helium liquefier during all collider and fixed target physics runs. The numbers in the table are slightly skewed in the low direction since only the run length in calendar time is conveniently known. (To be consistent with downtime typically quoted, the run length should be calendar time less scheduled downtime.).

The table shows that the downtime associated with the CHL was higher and with significantly more events, in early physics runs. Four major improvements were made to improve downtime.

1) Residual aluminum oxide dust from the original brazing of the plate-fin heat exchangers was blown out.
2) A redundant third compressor was commissioned.
3) A liquid helium pump was commissioned which allows pumped liquid helium from storage dewars to be added to the plant production during times of high satellite refrigerator demand.

4) The development of a spectrographic nitrogen detector, which could reliably measure down to 1 PPM. This led to better purification techniques and maintenance procedures.

Table 1 Central Helium Liquefier Downtime Versus Physics Run

Physics Run	**CHL Downtime**	**Run Length**	**# Events**	**CHL Downtime**
	[hours]	[hours]	[-]	[%]
980 GeV Collider Run II (to date)	54.1	37,584	5	0.14%
980 GeV Collider Engr. Run (2000)	30.2	2,736	1	1.10%
800 GeV Fixed Target (1999)	35.4	5,376	2	0.66%
800 GeV Fixed Target (1996/7)	13.7	9,600	2	0.14%
900 GeV Collider Run IB (1994/5)	29.5	19,104	2	0.15%
900 GeV Collider Run IA (1992/3)	32.3	6,528	3	0.49%
800 GeV Fixed Target (1991/2)	3.3	4,225	10	0.08%
800 GeV Fixed Target (1990)	4.1	4,703	1	0.09%
900 GeV Collider (1988/89)	12.8	8,280	4	0.15%
800 GeV Fixed Target (1987/8)	7.4	5,881	13	0.13%
900 GeV Collider (1987)	0.0	2,351	0	0.00%
800 GeV Collider (1985)	0.0	744	0	0.00%
800 GeV Fixed Target (1985)	62.1	5,447	18	1.14%
800 GeV Fixed Target (1984)	35.3	3,023	13	1.17%
400 GeV Fixed Target (1983/4)	60.2	3,433	12	1.75%

Analysis of downtime for other systems in the Tevatron can be misleading due to overlapping downtime with other systems. If a system has a known problem, but is able to continue operation, it is not uncommon for the problem to be corrected during downtime caused by another system. However, both, or more, systems are charged with the downtime. This accounting system is helpful to keep track of all work performed on the system, but results in unrealistic total downtime figures due to the multiple counting.

Table 2 shows the downtime associated with the Tevatron satellite refrigeration system. The downtime for this system is higher than for CHL, as expected, due to the high number of systems (24) and the use of reciprocating expansion engines. It is interesting that the downtime is not a consistently correlated with physics type (Fixed Target versus Collider). With the constant ramping of the magnets and the greater beam manipulation, one would expect this mode of physics to place a greater burden on the cryogenic system reliability.

Satellite refrigerator downtime was higher during early physics runs of the Tevatron. Two major improvements were made to improve downtime.

1) Improvements in alignment and materials used in our reciprocating expanders have considerably lengthened the mean time between failures. Operating times of one year are now common, allowing expander maintenance to take place during scheduled long shutdowns.

2) Parts used to clamp conductor within dipole magnets were coming loose and becoming wedged within magnet quench relief valves. Parts were secured during 1984 and 1989 dipole repair shutdowns.

Table 2 Tevatron Satellite Refrigerator Downtime Versus Physics Run

Physics Run	**TCRYO Downtime**	**Run Length**	**# Events**	**TCRYO Downtime**
	[hours]	[hours]	[-]	[%]
980 GeV Collider Run II (to date)	458.6	37,584	152	1.22%
980 GeV Collider Engr. Run (2000)	88.8	2,736	24	3.25%
800 GeV Fixed Target (1999)	163.6	5,376	97	3.04%
800 GeV Fixed Target (1996/7)	78.7	9,600	191	0.82%
900 GeV Collider Run IB (1994/5)	190.6	19,104	166	1.00%
900 GeV Collider Run IA (1992/3)	61.9	6,528	47	0.95%
800 GeV Fixed Target (1991/2)	44.9	4,225	100	1.06%
800 GeV Fixed Target (1990)	45.5	4,703	97	0.97%
900 GeV Collider (1988/89)	74.5	8,280	47	0.90%
800 GeV Fixed Target (1987/8)	77.8	5,881	136	1.32%
900 GeV Collider (1987)	30.4	2,351	16	1.29%
800 GeV Collider (1985)	7.0	744	8	0.94%
800 GeV Fixed Target (1985)	118.5	5,447	280	2.18%
800 GeV Fixed Target (1984)	187.6	3,023	420	6.21%
400 GeV Fixed Target (1983/4)	204.3	3,433	408	5.95%

It is encouraging that the current Collider Run II has not experienced higher satellite refrigerator downtime. Operation of the Tevatron at 980 GeV required the installation of twenty-four cold helium compressors. To date, operating in this mode has not adversely affected downtime.

Table 3 gives the downtime associated with quenches in the Tevatron. It is surprising that fixed target physics did not consistently register more downtime than colliding beam physics. With the constant beam manipulation associated with fixed target operation, a higher number of quenches is realized in fixed target physics. Having a similar amount of downtime for quenching in collider and fixed target modes implies that a longer recovery time is experienced in collider mode. This may be due to some level of shot setup, or preparation for shot setup, being charged to the quench recovery. In the 980 GeV collider operation, longer quench recoveries are expected in order to restore the magnet string to the lower temperature required to operate at higher energy.

Space constraints within the Tevatron tunnel precluded the ability to install a quench gas recovery header, as used in the HERA accelerator. As a result, the majority of helium relieved from magnets on a high field quench is relieved to atmosphere. The high heat load of a warm iron magnet design also results is much faster loss of helium during power outages.

Table 3 Tevatron Quench Downtime Versus Physics Run

Physics Run	**TQUEN Downtime**	**Run Length**	**# Events**	**TQUEN Downtime**
	[hours]	[hours]	[-]	[%]
980 GeV Collider Run II (to date)	1,251.4	37,584	477	3.33%
980 GeV Collider Engr. Run (2000)	79.8	2,736	41	2.92%
800 GeV Fixed Target (1999)	99.6	5,376	82	1.85%
800 GeV Fixed Target (1996/7)	208.8	9,600	312	2.18%
900 GeV Collider Run IB (1994/5)	594.5	19,104	247	3.11%
900 GeV Collider Run IA (1992/3)	123.3	6,528	56	1.89%
800 GeV Fixed Target (1991/2)	70.1	4,225	89	1.66%
800 GeV Fixed Target (1990)	110.7	4,703	121	2.35%
900 GeV Collider (1988/89)	194.5	8,280	112	2.35%
800 GeV Fixed Target (1987/8)	211.5	5,881	215	3.60%
900 GeV Collider (1987)	60.5	2,351	45	2.57%
800 GeV Collider (1985)	13.8	744	10	1.85%
800 GeV Fixed Target (1985)	140.4	5,447	219	2.58%
800 GeV Fixed Target (1984)	134.6	3,023	140	4.45%
400 GeV Fixed Target (1983/4)	117.9	3,433	219	3.43%

Cryogenic Operations

The CHL was designed and built in the mid to late 1970s. Control of the plant was accomplished using industrial process controls. The sophistication of the controls was limited to the steady-state operation of the plant. Warm-up, cool-down and upset conditions require operator intervention. As a result, cryogenic operational crews are present around the clock.

The twenty-four satellite refrigerators were originally designed with local instrumentation and pneumatic controllers. Early on, the satellite control scheme was changed to an in-house designed computer based process control system which was tied into the overall accelerator control system for remote resources, control and monitoring. As a result, no cryogenic operators are necessary for the satellite refrigerators. Instead, they are monitored by the accelerator operators who contact cryogenic on-call personnel when necessary.

Modern cryogenic systems can be designed to operate unattended. For such a system, care needs to be given to incorporate adequate software intelligence to ensure equipment protection during all plausible upset conditions.

Table 4 compares operational personnel for various large scale cryogenic accelerator systems. The refrigeration systems for the Tevatron, RHIC, and HERA were designed and built in the late 1970s to mid 1980s. The refrigeration system for CEBAF was designed in the late 1980s and built in the early 1990s. Experience gained, during this time, in the operation of large cryogenic plants, coupled with significant advances in process control are evident in the operational personnel requirements

Table 4 Comparison of Cryogenic Operations in Large Accelerators

	CEBAF[1]	**RHIC**[2,3]	**HERA**[1]	**Tevatron**[2]
Operators (Lab)	1	11	11	15
Operators (Contractor)	0	0	7	0
Operations Support Staff	1	3	1	3

Notes:
1. Data from 1996
2. Data from 2005
3. Cryogenic system originally designed for ISABELLE and CBA

Helium Loss

Opportunities to loose helium are related to the number of bolted, screwed or relieved connections to atmosphere, more so than the size of the connection. The large number of refrigerators in the Tevatron cryogenic system makes helium loss a challenge.

Space constraints within the Tevatron tunnel precluded the ability to install a quench gas recovery header, as used in the HERA accelerator. As a result, the majority of helium relieved from magnets on a high field quench is relieved to atmosphere. The high heat load of a warm iron magnet design also results is much faster loss of helium during power outages. A site wide power outage results in a complete loss of helium inventory (750,000 scf) in about 45 minutes.

Table 5 Comparison of Cryogenic Helium Losses in Large Accelerators

	CEBAF[1]	**RHIC**[2,3]	**HERA**[1]	**Tevatron**[2]
Number of Refrigerators	3	1	3	25
Recover Quench Gas	NA	Yes	Yes	No
Losses (scf/day)	11,700	12,000	2,800	30,000
Losses per Refrigerator (scf/day)	3,900	12,000	933	1,200

Notes:

scf = standard cubic feet

1. Data from 1996
2. Data from 2005
3. Cryogenic system originally designed for ISABELLE and CBA